

Exploring Strange Origin of Dirac Neutrino Masses at Hadron Colliders

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- The Standard Model does not include right-handed singlet neutrino fields, and so has massless neutrinos
 - With right-handed singlet neutrinos, the mass-generating terms would be allowed
- The existence of neutrino oscillation implies that (at least two) neutrino masses are non-zero
- Cosmological bounds place an upper limit on the sum of neutrino masses of ~ 0.12 eV
- Why do neutrinos have such extremely small masses?

A Different Approach to Neutrino Masses

- We will accept the existence of right-handed singlet neutrinos to support Dirac neutrino masses
- The following effective operator, with Standard Model and singlet neutrino fields only, can generate Dirac neutrino mass:

$$O_D = \zeta \frac{[\bar{Q}^i s] \epsilon^{ij} [\bar{L}^j \nu_R]}{M_D^2} + \text{H.C.} \quad (1)$$

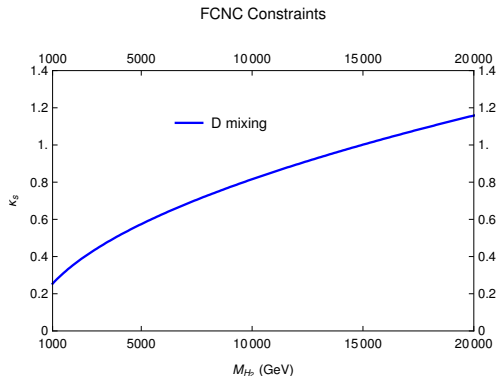
- The light quark condensates $\langle \bar{q}q \rangle \sim -(300 \text{ MeV})^3$ provides EWSB
- Generating $\sim 0.1 \text{ eV}$ neutrino masses requires $M_D \sim 16 \text{ TeV}$
 - π^+, K^+ decays to $e^+ \nu$ constrain similar scale operators with d and u quarks, thus necessitating the use of the strange quark
- So: how can we generate this sort of operator?

A 2HDM Model

- We use two Higgs doublets: H_1 and H_2
- H_1 will be the sole doublet that gets a vev
 - It generates quark, charged lepton, W/Z masses exactly as in the SM
 - The Z_2 symmetry forbids the usual sort of neutrino mass terms
- H_2 will couple only to neutrinos and the strange quark
 - We will call the strange quark Yukawa coupling κ_s
 - For an H_2 mass of M_{H_2} , the mass-basis neutrino Yukawa couplings will be

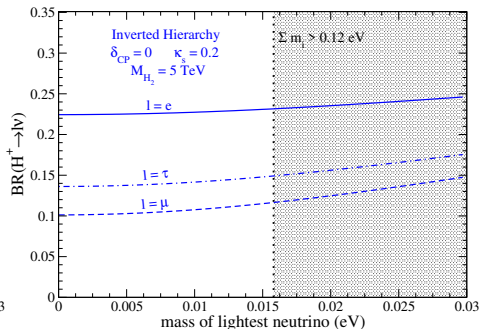
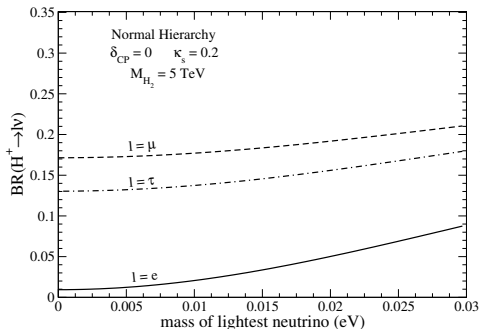
$$\kappa_{\nu,i} = \frac{M_{H_2}^2}{\kappa_s \langle \bar{s}s \rangle} m_i \quad (2)$$

- The matrix of neutrino Yukawa couplings is then $V_{PMNS} K_\nu$ with $K_\nu = \text{diag}(\kappa_{\nu,1}, \kappa_{\nu,2}, \kappa_{\nu,3})$



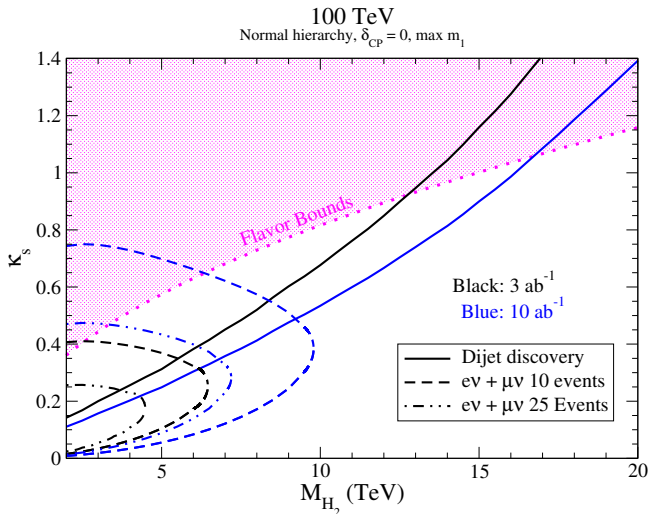
- $D - \bar{D}$ mixing is the primary constraint on κ_S
 - These constraints beat the reach of the LHC; need to go to 100 TeV
- $D_S^+ \rightarrow e^+ \nu$ can constrain this general mass generating mechanism
 - Current limits come from Belle; we don't expect Belle II to approach sensitivity to our model

Charged Higgs Branching Ratios



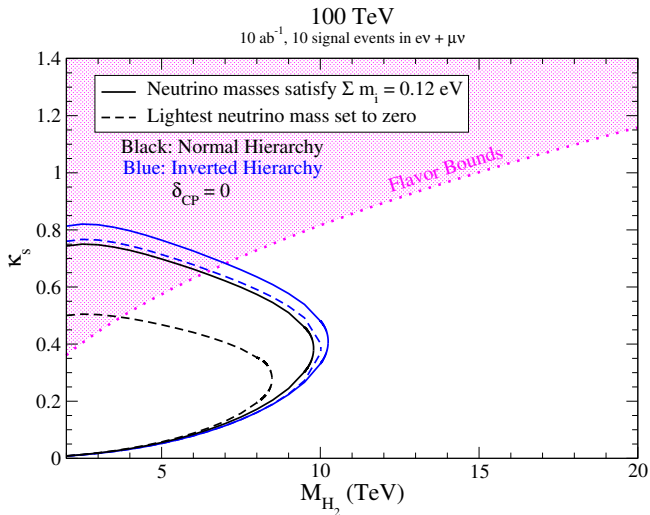
- Charged Higgs can decay to dijet, or charged lepton and neutrino
- The branching ratios $BR(H \rightarrow e\nu, \mu\nu, \tau\nu)$ depend on mass hierarchy, slightly on absolute neutrino mass scale
 - In normal hierarchy, $\mu\nu$ is the dominant lepton final state
 - In inverted hierarchy, $e\nu$ is the dominant lepton final state

100 TeV Discovery Potential



- Dijets and $l\nu$ provide orthogonal discovery potential
- Shown: normal hierarchy, saturating cosmological neutrino mass

Effects of the Mass Hierarchy



- The neutrino mass hierarchy and absolute mass scale matter for the collider phenomenology

- Chiral condensates in QCD provide another (small) source of electroweak symmetry breaking
- A heavy Higgs doublet can connect this symmetry breaking to the neutrino sector
- Strange quark couplings are a viable path for neutrino mass with interesting collider signatures
 - Dijet signal
 - Lepton plus missing energy
- Charged Higgs branching ratios are sensitive to the neutrino mass hierarchy

Thank you!

Backup

A 2HDM Flavor Model

- We have the following general Yukawa sector (flavor indices suppressed):

$$\sum_{a=1}^2 -\lambda_u^a \bar{Q} \epsilon H_a^* u - \lambda_d^a \bar{Q} H_a d - \lambda_\nu^a \bar{L} \epsilon H_a^* \nu_R - \lambda_\ell^a \bar{L} H_a \ell + \text{H.C.} \quad (3)$$

- We introduce a Z_2 symmetry under which H_2 and ν_R are odd, other SM fields are even
- This Z_2 eliminates neutrino couplings to H_1 and the ordinary fermion mass generation
- But it also eliminates non-neutrino couplings to H_2 , including the s quark couplings that we want
 - We can spontaneously break the Z_2 with a scalar ϕ , and use a dim 5 operator like $\frac{\phi H_2 \bar{Q} s}{\Lambda}$ where $\langle \phi \rangle \neq 0$
 - This can come from e.g. a UV model with a heavy vector-like quark with the quantum numbers of the right-handed s